Dynamic Testbed Demonstration of WFIRST Coronagraph Low Order Wavefront Sensing and Control (LOWFS/C)

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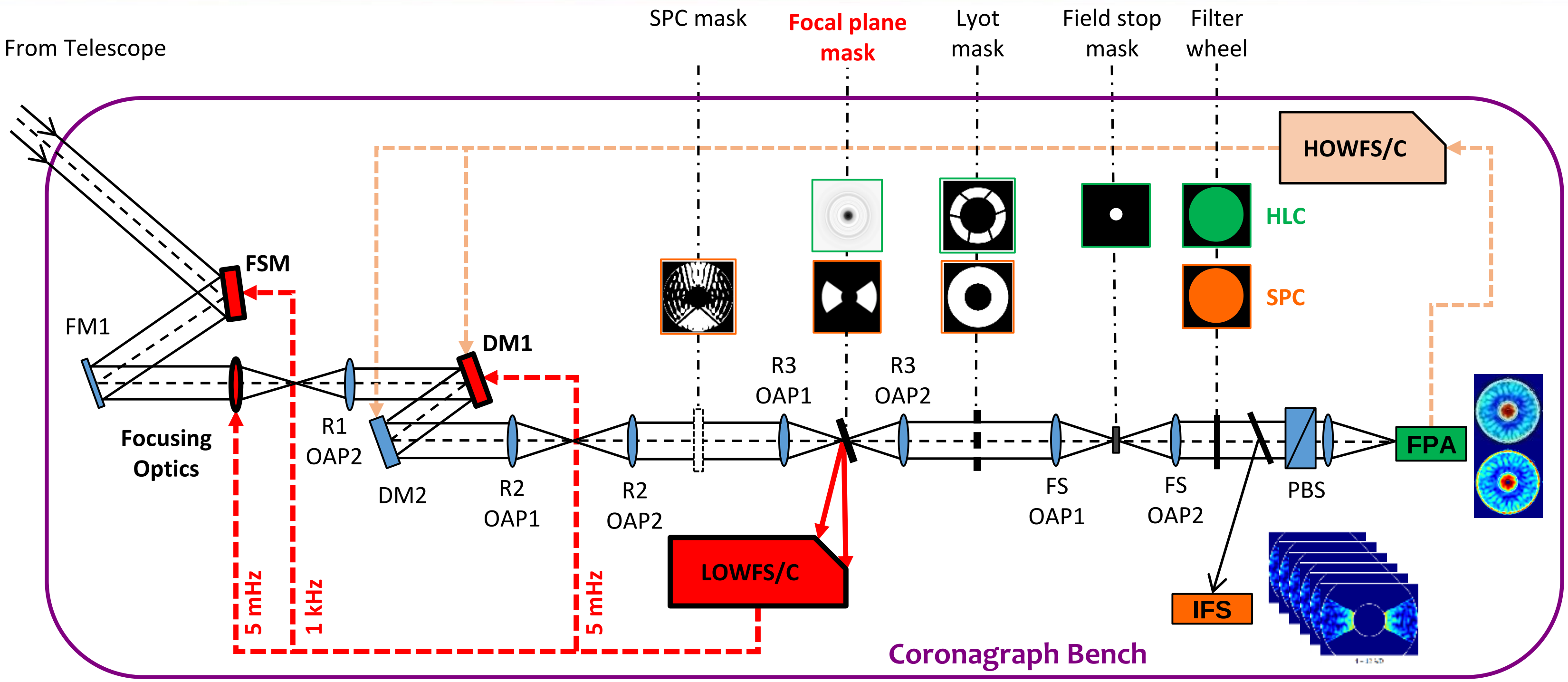
Outline

- Low order wavefront sensing and control (LOWFS/C) subsystem for WFIRST Coronagraph
- Occulting Mask Coronagraph (OMC) dynamic testbed
- LOWFS/C sensor performance and calibration
- Coronagraph and LOWFS/C closed loops demonstration with WFIRST like dynamic wavefront disturbances
- Compare LOWFS/C performance with model prediction
- Conclusion and future work

LOWFS/C Overview

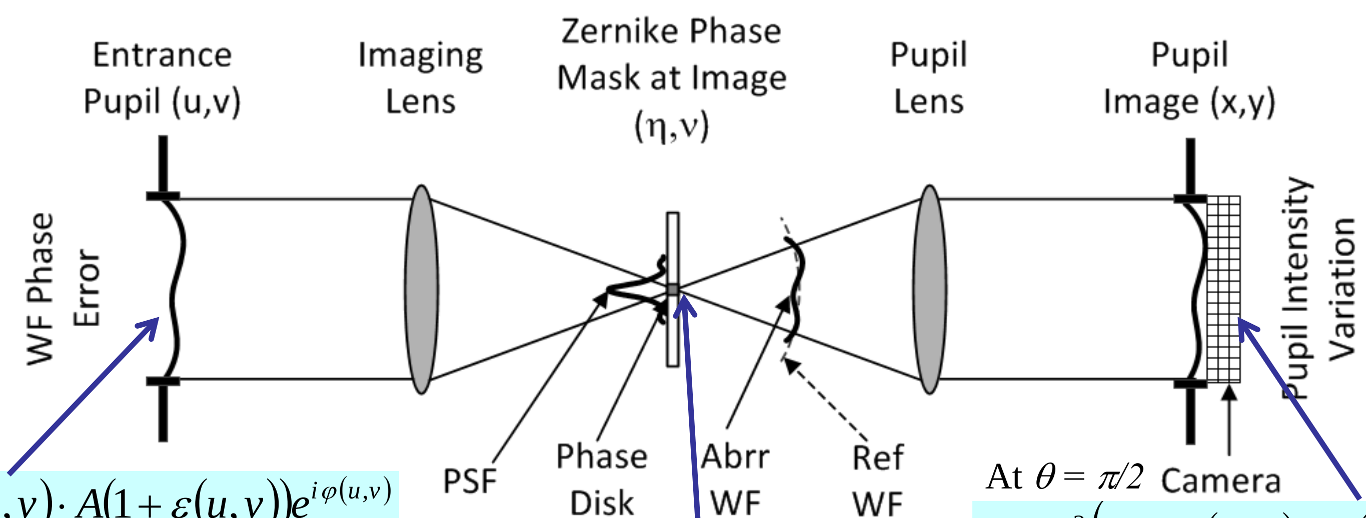


- LOWFS/C subsystem measures and controls line-of-sight (LoS) jitter and drift as well as the thermally induced low order wavefront drift
  - LoS: drift (< 2 Hz): ~14 mas, tonal jitter: ~14 mas
  - WFE: drift (~10^{-3} Hz): ~0.5 nm (RMS), dominant by focus as well as astigmatisms and comas from the telescope optics rigid body motion
- Differential sensor referenced to coronagraph wavefront control: maintains wavefront established for high contrast (HOWFS/C using EFC)
- Uses rejected starlight from occulter which reduces non-common path error
- LOWFS/C telemetry can be used for coronagraph data post-processing

Zernike Wavefront Sensor Concept

- **Zernike WFS (ZWFS) measures wavefront error (WFE) from interference between the aberrated WF and the reference WF generated by a phase dimple (diameter ~ λ/D)**
  - At phase shift of π/2, pupil image brightness variation is proportional to the WFE: $\Delta I \sim \pm 2\varphi$
  - Same principle as Zernike phase contrast microscope
- **ZWFS uses linearized differential image to sense the delta WFE**
  - ZWFS sensed pupil is imaged to CCD at 16x16 pixels for sensing WFE up to spherical aberration Z11
  - 128 nm spectral band (throughput vs. accuracy trade-off)

- **ZWFS converts pupil phase variation into intensity variation on the LOWFS camera**



$$E(u,v) = P(u,v) \cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$

At $\theta = \pi/2$

$$I = A^2\left(1 + 2\varphi(x,y) + \varepsilon(x,y)^2 + \varphi^2\right)$$

$$\hat{E}(\eta,\upsilon) = A \cdot CPSF(\eta,\upsilon)e^{i\theta} + A \cdot CPSF(\eta,\upsilon) \otimes F\{\varepsilon(u,v) + i\varphi(u,v)\}$$

$$Z = \alpha^{-1}(K^T K)^{-1} K^T \bullet \Delta I$$

ZWFS sensing algorithm

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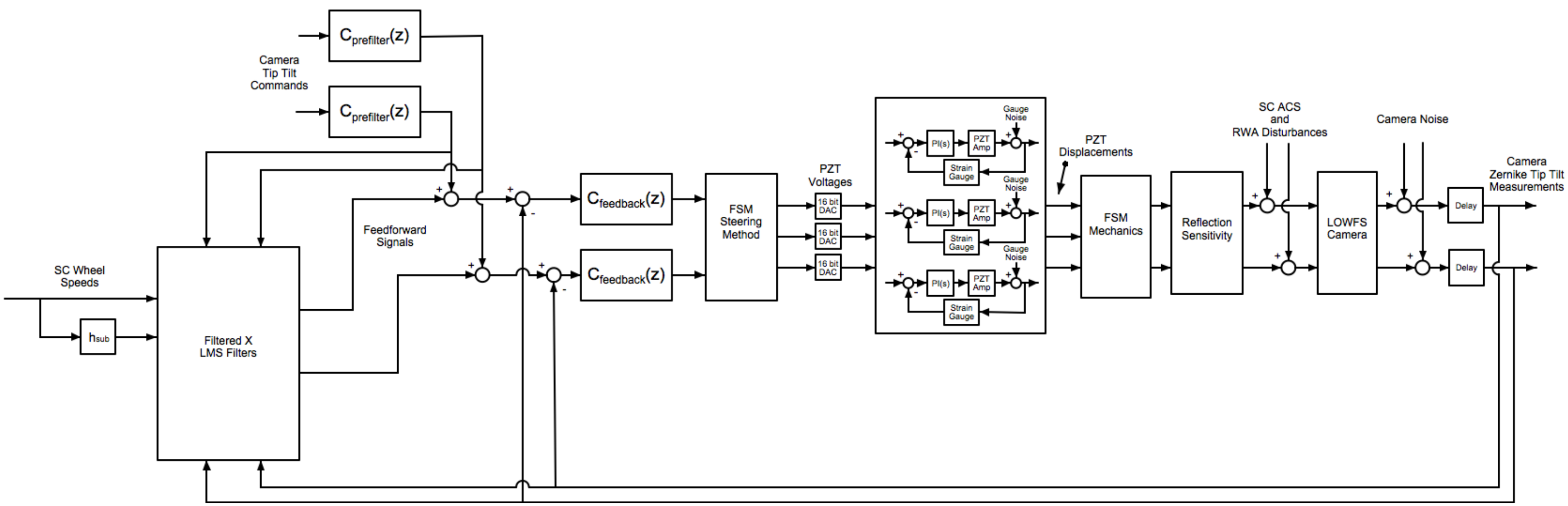
LOWFS/C Line-of-Sight Control Approach

- **Line-of-sight control uses both feedback and feedforward loops**
- **Feedback path to cancel slow ACS LoS drift**
  - LOS loop is shaped for **optimal rejection of the ACS disturbance and LOWFS/C sensor noise.** This is done by balancing the error contribution from sources of jitter, camera noise, and LoS drift from ACS
- **Feedforward path to cancel high frequency tonal LoS jitter from RWAs**
  - RWA speeds used to determine the disturbance frequencies
  - A least-mean-square (LMS) filter estimates the gain and phase of the tonal disturbances
  - Correction commands are directly sent to FSM

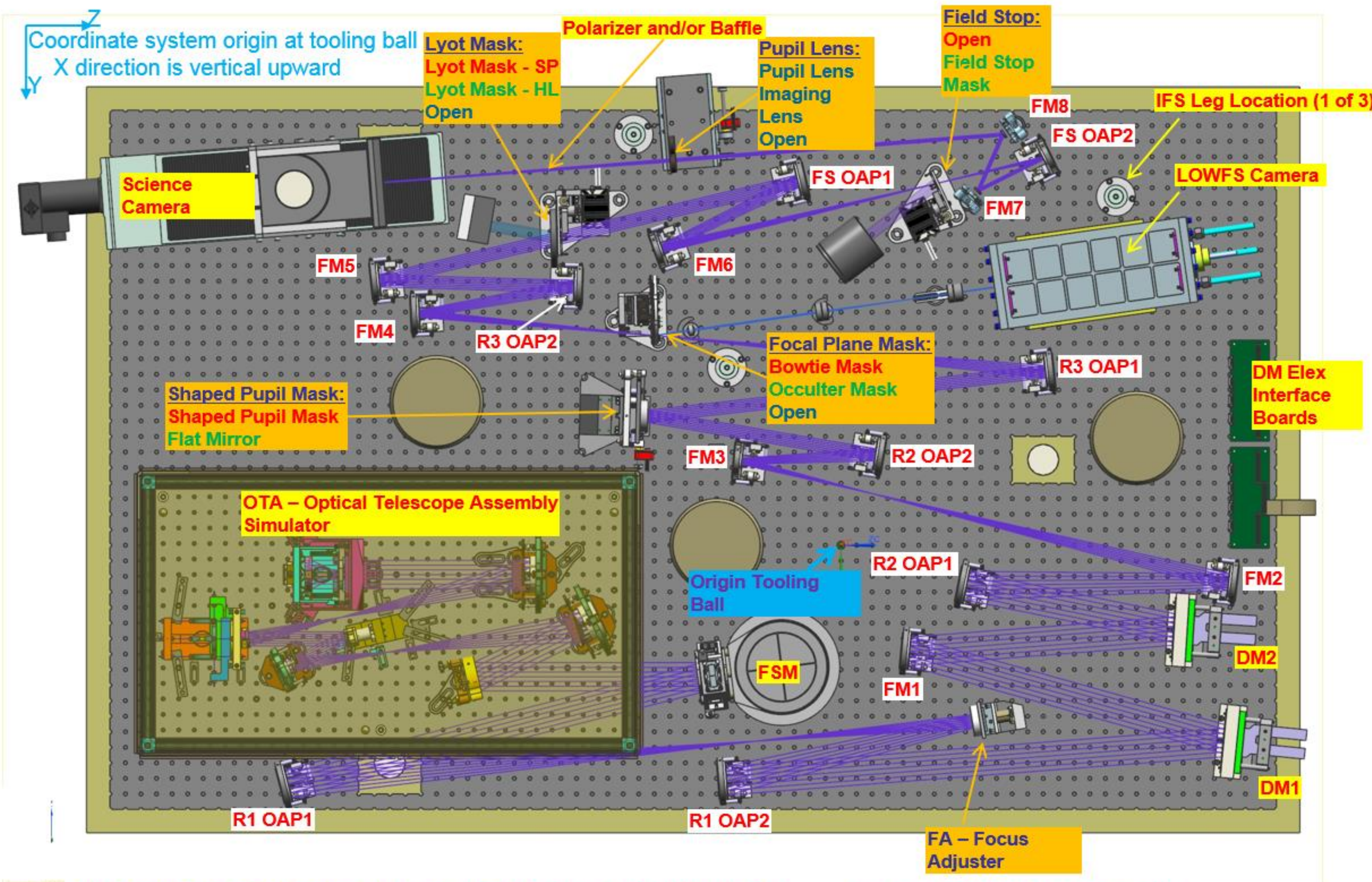


LoS Feedforward **LoS Feedback Loop**

Occulting Mask Coronagraph (OMC) Dynamic Testbed

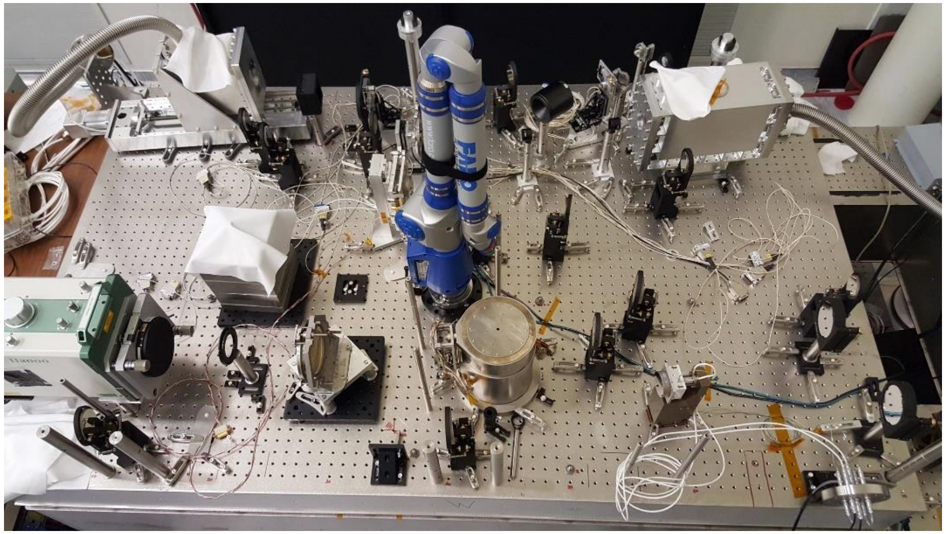
- Testbed with masks and stops support two coronagraph modes (Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)) on the common optics – similar to WFIRST flight coronagraph instrument – with mechanisms to remotely switch between these two modes.
- Optical telescope assembly simulator (OTA-S) with a representative obscured pupil that can produce on-orbit dynamic disturbances such as observatory pointing drift and jitter and thermal drifts
- Low-order wavefront sensor that uses the rejected “star” light and is capable of both sensing sub-angstrom level wavefront errors and controlling a fast-steering mirror, focus adjustment, and a deformable mirror to reduce these disturbances
- Stable, extensively modeled optical mounts to enable the validation of coronagraph structural, thermal, optical, performance (STOP) models.
- Improvements made to the vacuum tank’s mechanical isolation, thermal insulation, active thermal control, and stray light control

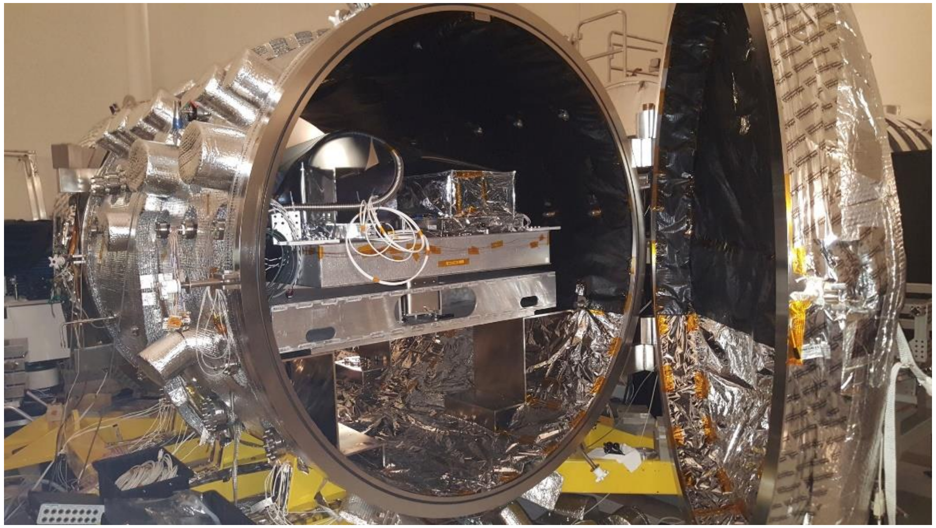
OMC Dynamic Testbed

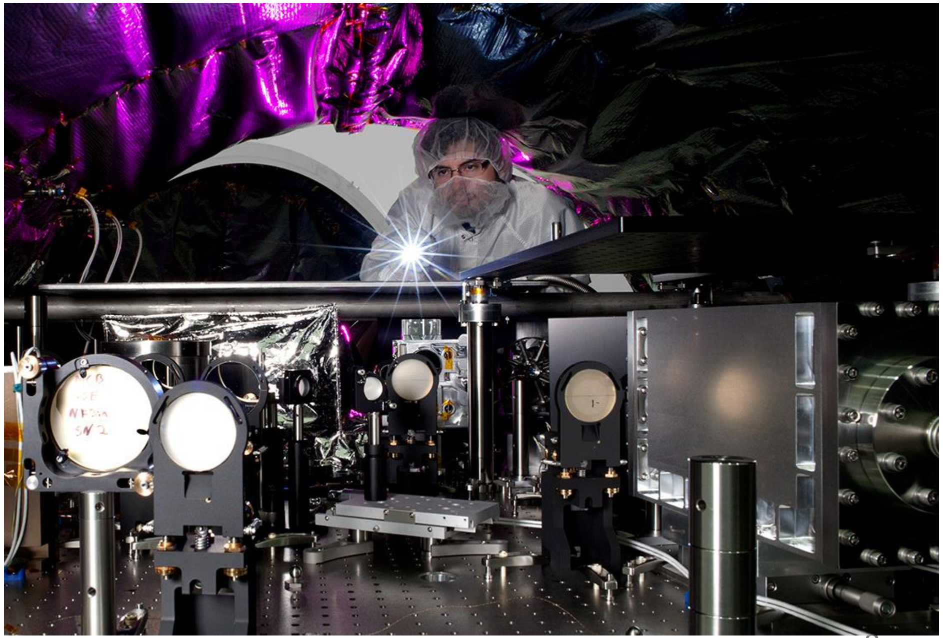


Mechanisms in Orange boxes: red is shaped-pupil mode and green is hybrid Lyot mode
Table is invar 78” x 48”

OMC Dynamic Testbed

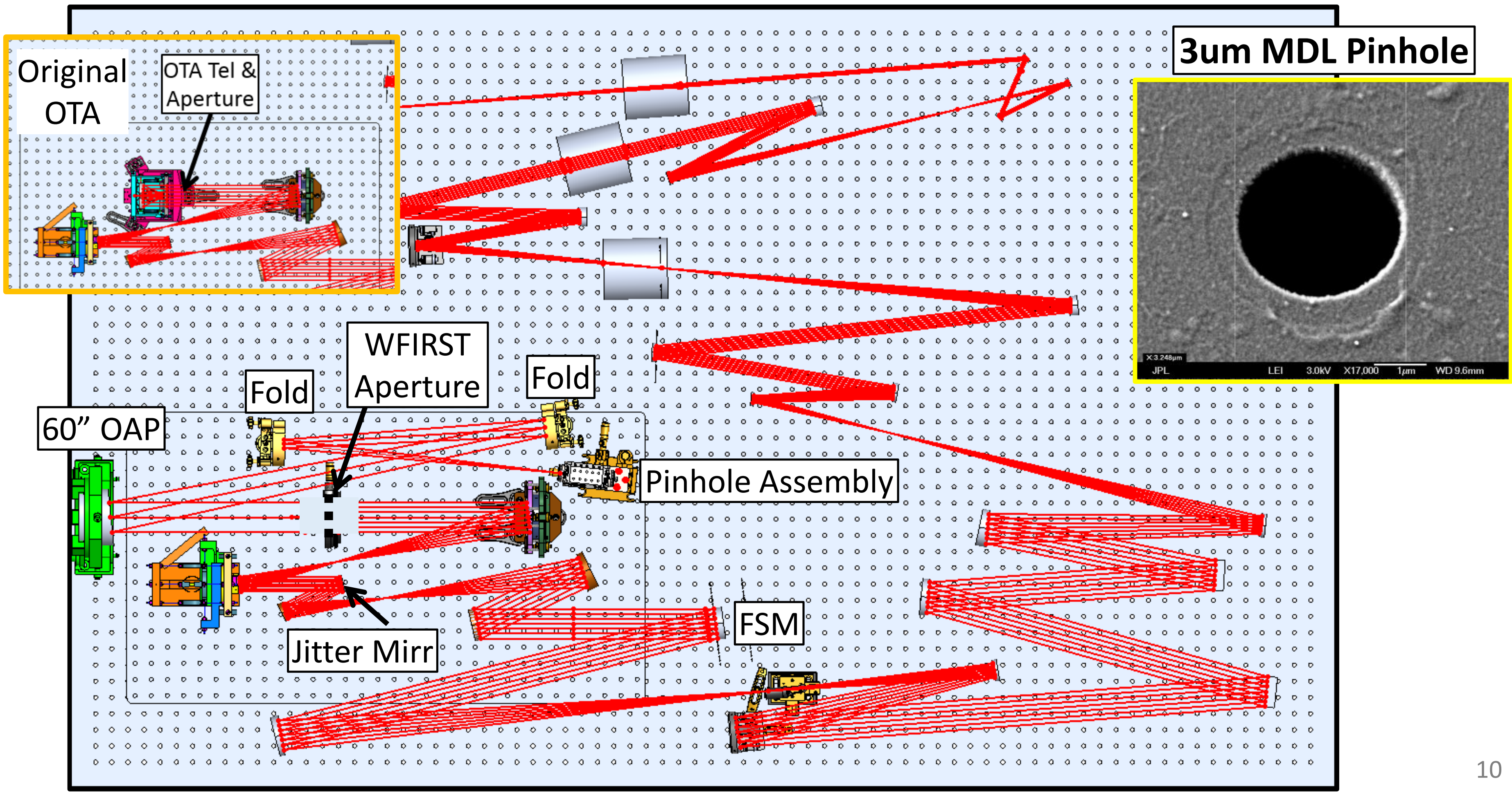




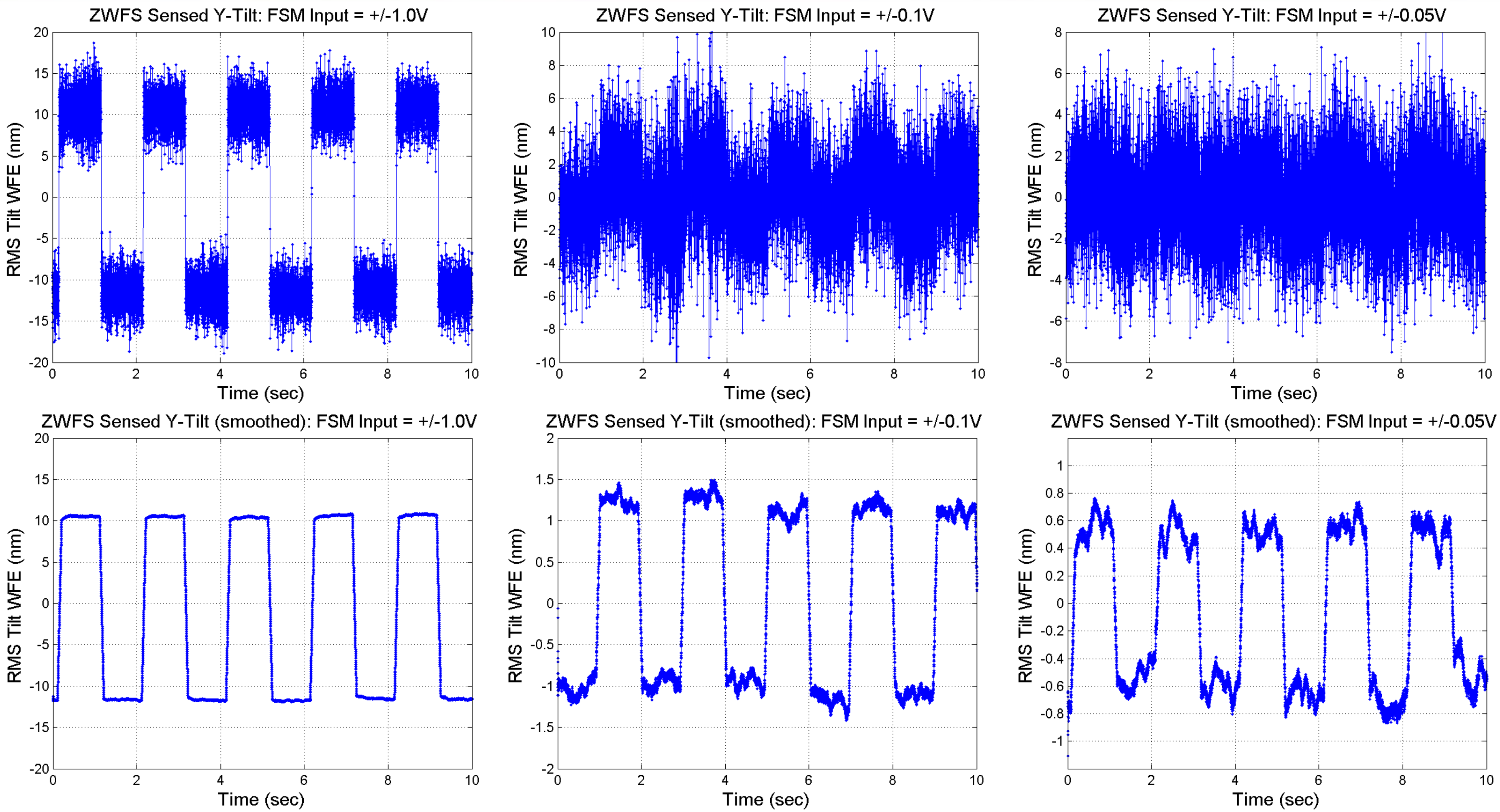


Modified OTA Simulator

- F/33.3 injection with 60” OAP: significantly reduced (~5X) pseudo star size
- MDL pinhole: thin, non-metallic, etched in silicon at MDL, excellent dimension and edge
- Pinhole on a stage with a linear motor for focus disturbances.
    - Scale = 1 nm RMS focus / 32 um linear motor motion
- A freestanding pupil mask in collimated beam, replacing the miniature OTA Telescope



ZWFS Results: Line of Sight Error Sensing



Mean Sep=22.1 nm=7.7 mas

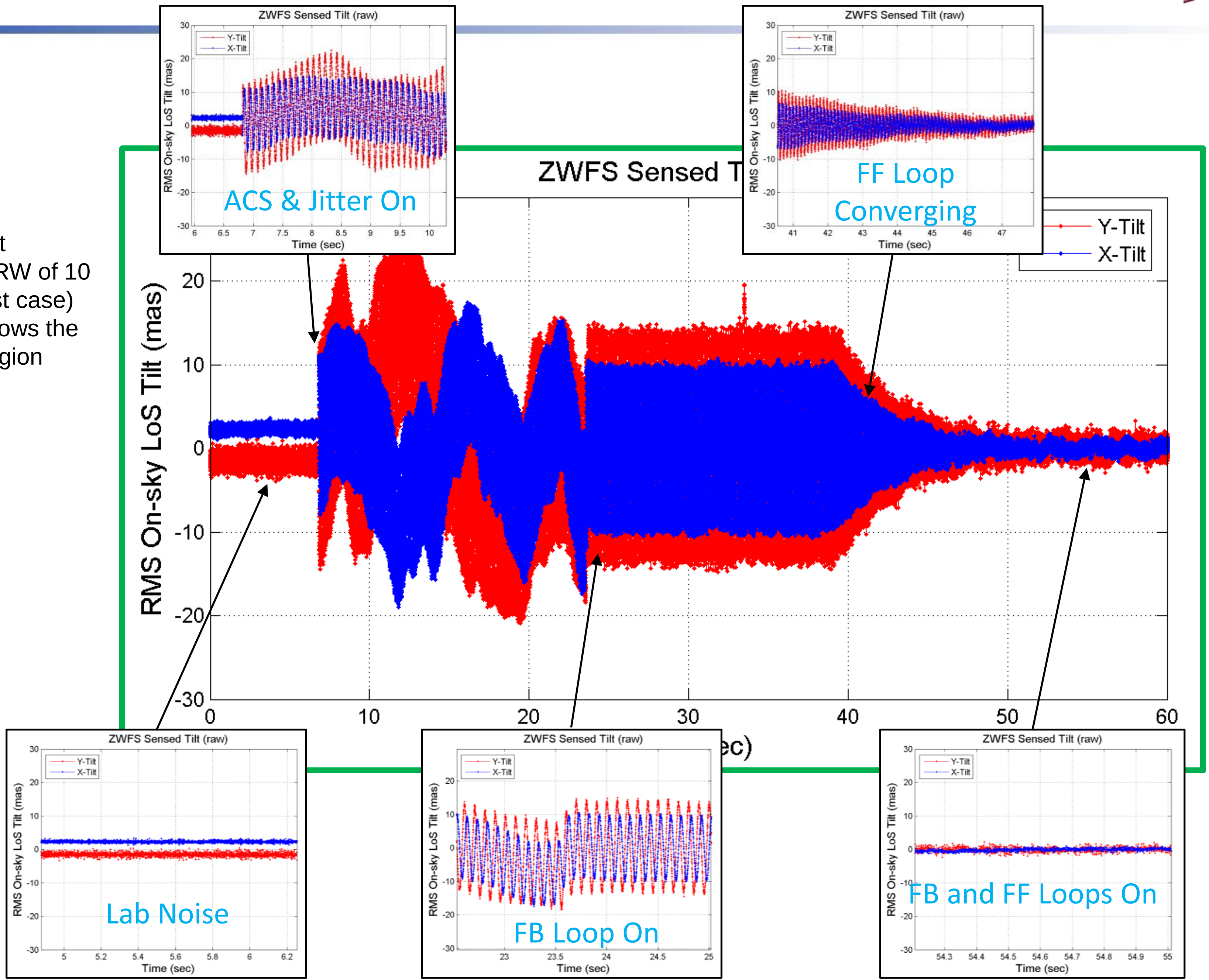
Mean Step=2.2 nm=0.77 mas

Mean Step=1.2 nm=0.38 mas

- Sensor clearly detects +/- 0.19 mas on-sky signal (right column)
- ZWFS sensed tilt WFE matches calibrated input to within 8%

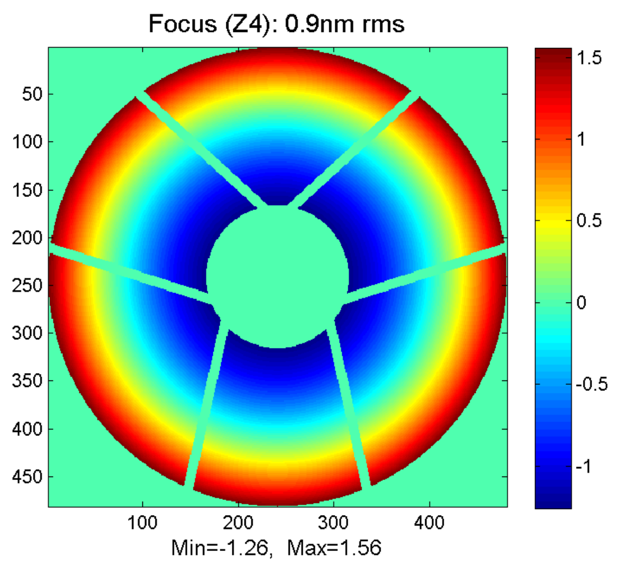
LOWFS/C LoS Feedback and Feedforward Loops Demo

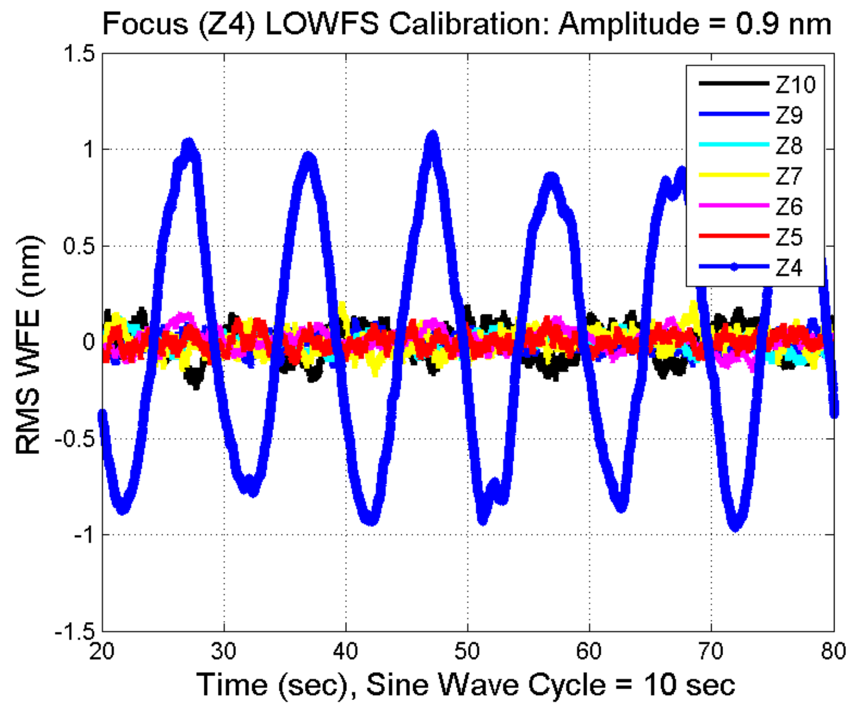
- Disturbance:
- ACS LoS drift
- LoS jitter @ RW of 10 rev/sec (worst case)
- Small plot shows the zoomed in region



ZWFS Calibration: Focus

- **OTA Simulator generates sinusoidal focus mode (Z4) with PZT-induced telescope motion**
- **Input DAC amplitude 0.2 V is equivalent to 0.9 nm from OTA-S Zygo calibration**
- **LOWFS sensed applied focus (Z4) disturbance**
  - LOWFS sensor data averaged (1 sec box car) to remove the detector noise
- **The cross talk among low order modes is small**

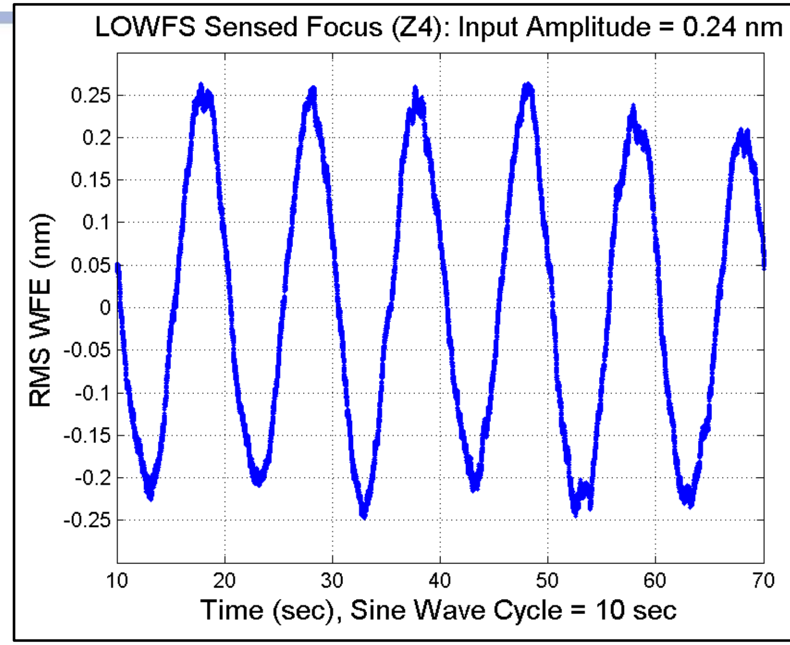


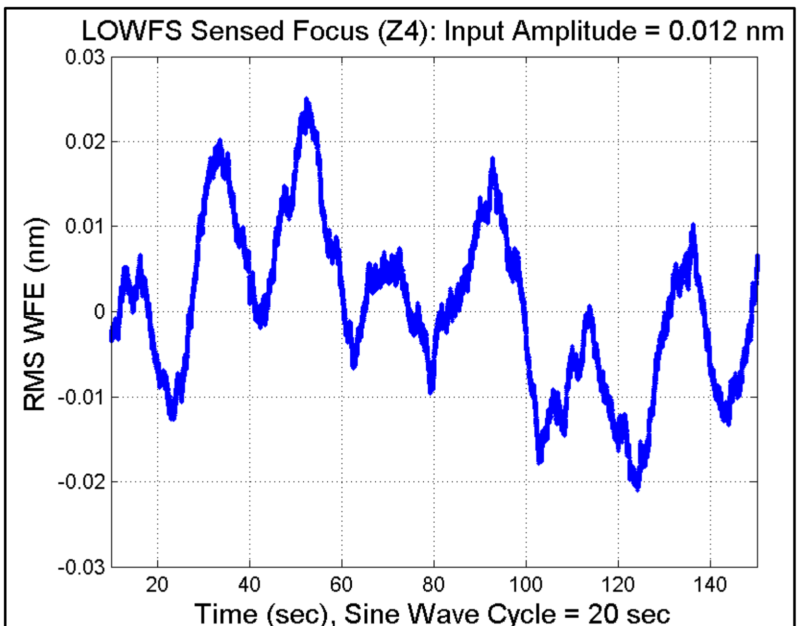


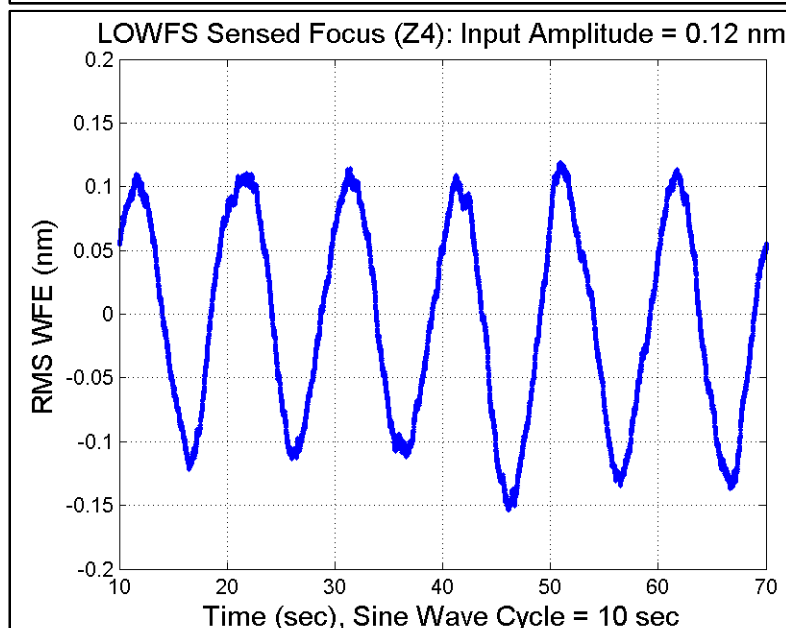
LOWFS measurements match independently calibrated OTA simulator

LOWFS Sensitivity: Focus

- **Reduced amplitude of OTA-S focus disturbance to create a small focus modulation for LOWFS sensor**
  - Increase modulation cycle period for more frame averaging to reduce sensor noise
  - Signals averaged to reduce noise and detrended to remove testbed focus drift
  - Average: 1, 2, 10 seconds for the plots
- **LOWFS can see focus as small as 12 pm (rms)!**

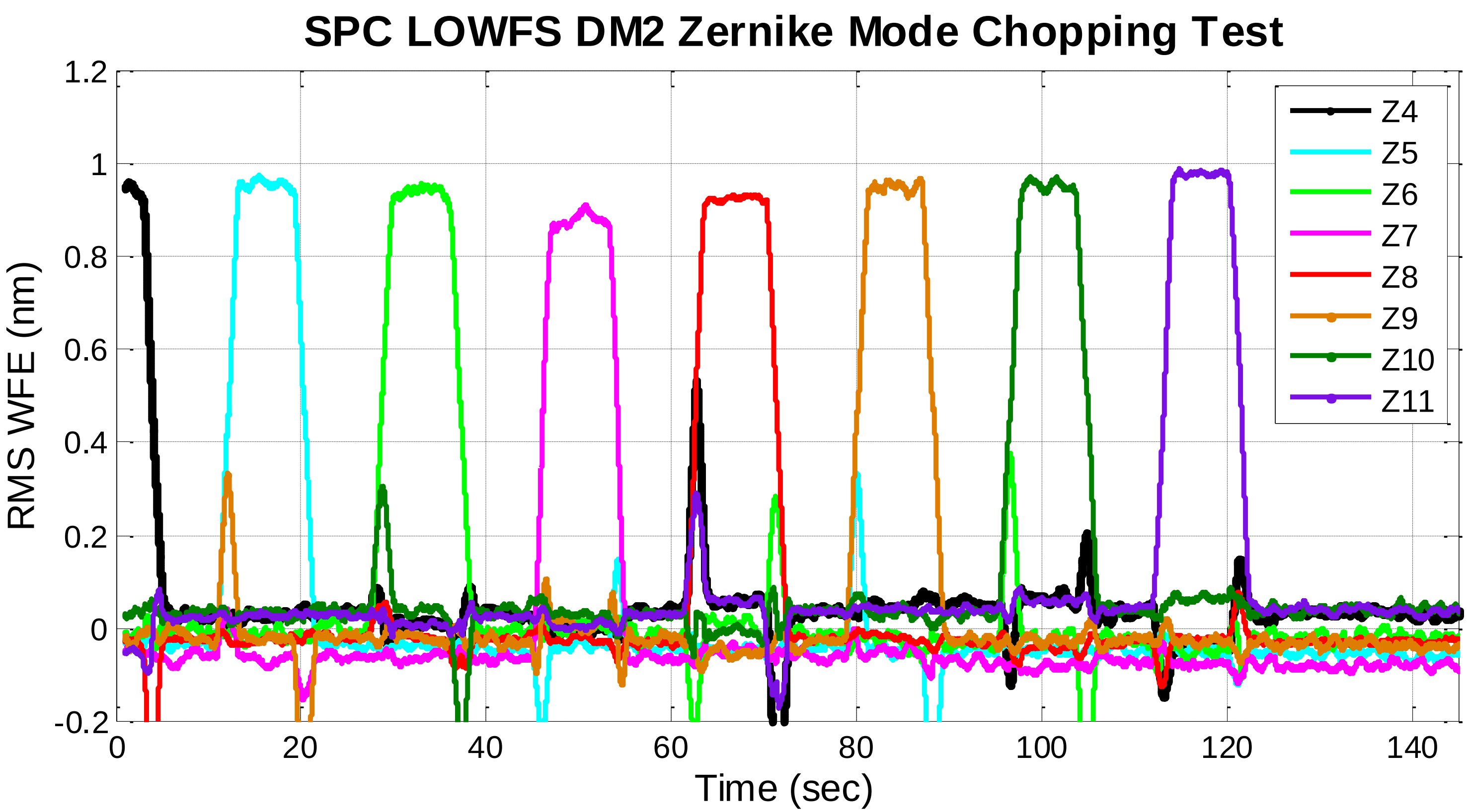






ZWFS Low Order Mode Calibration: Using DM #2

- One of OMC's DM is used to calibrate the LOWFS sensor
- Calibration is used to build empirical wavefront reconstructor for LOWFS to minimize the cross talk
- Plots shows LOWFS sensed Zernike mode signal when 1 nm (rms) of each Zernike mode is alternatively applied to the DM #2

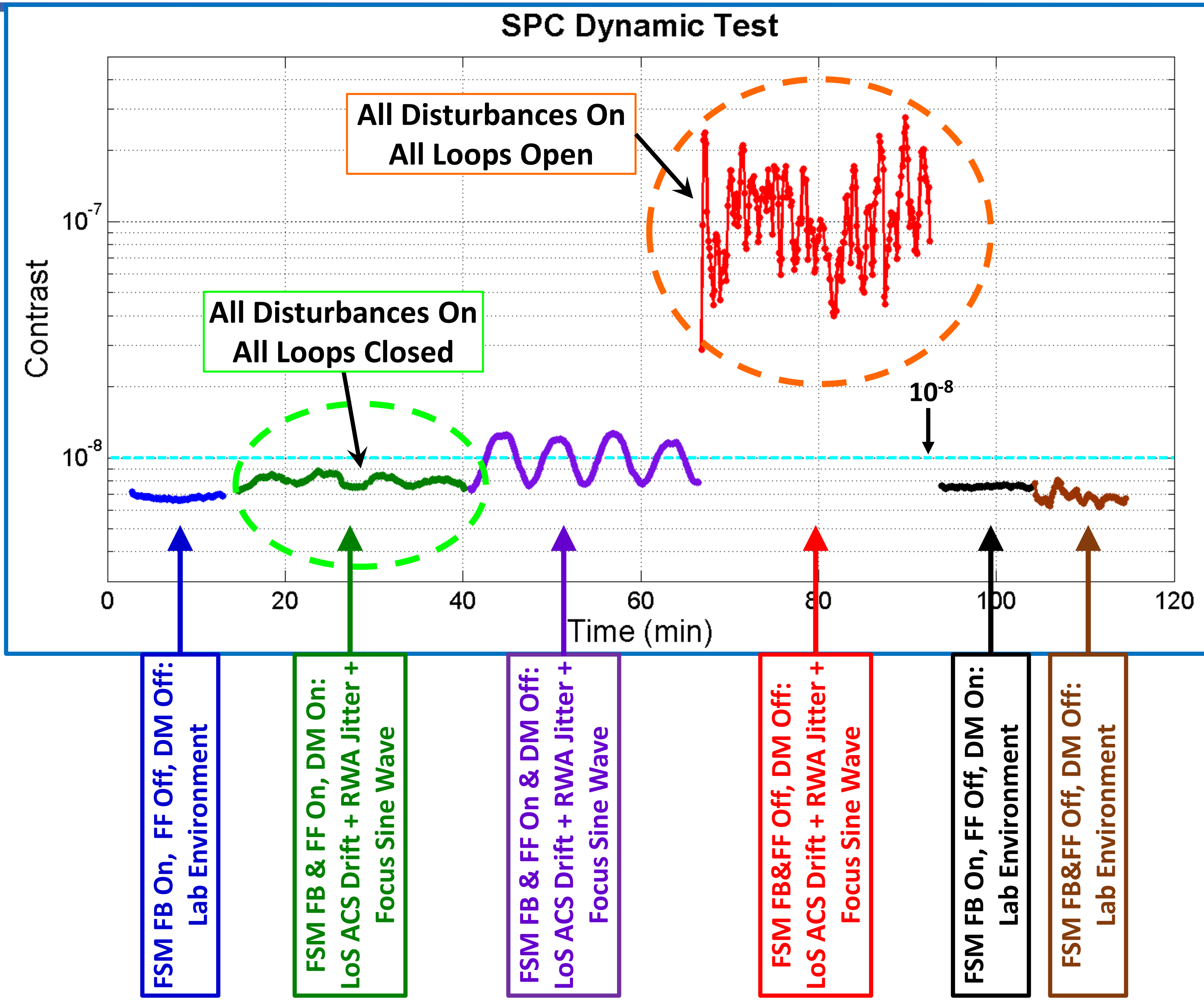


LOWFS/C Dynamic Test

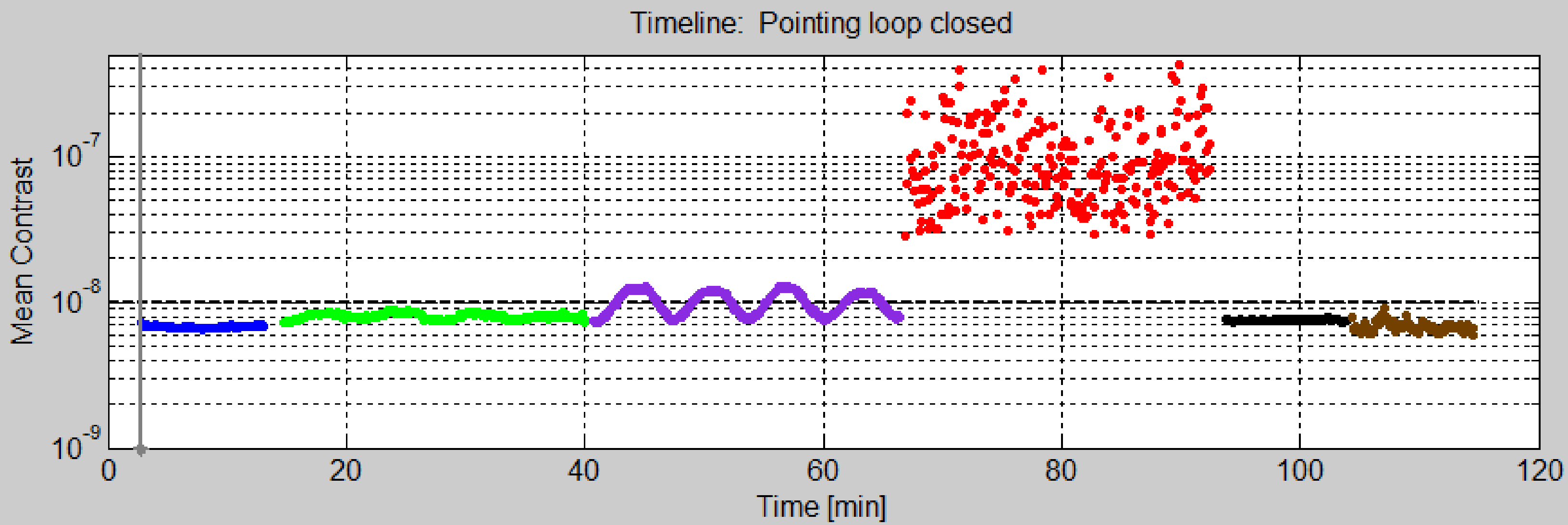
- **HLC/SPC dynamic test uses OTA-S to generate pointing and focus disturbances WFIRST would experienced on-orbit and LOWFS/C sensing & correction.**

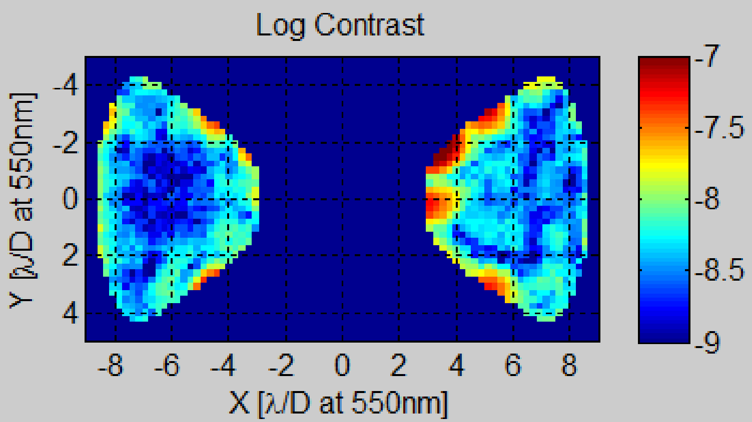
- Coronagraph Modes: Shaped Pupil and Hybrid Lyot Coronagraph (SPC and HLC)
  - Coronagraph contrast recorded with a 10% bandwidth filter centered at 550 nm.
- Line-of-sight Error Injected: 14 mas rms drift + CBE line of sight jitter at 600 rpm wheel speed (72 harmonic tones)
  - LoS error injected by OTA Simulator's Jitter Mirror (JM)
  - LoS error corrected by OMC's Fast Steering Mirror (FSM) with both feedback and feedforward loops
- Low Order WFE Injected: ±1 nm (SPC) and ±0.5 nm (HLC) focus disturbance. The amplitude is 4X and 2X worse than expected WFIRST thermal drift.
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec (12.5 min). The focus disturbance is much faster (~100X) than anticipated WFIRST thermal drift speed
  - Focus corrected by one of OMC's deformable mirrors (DM).

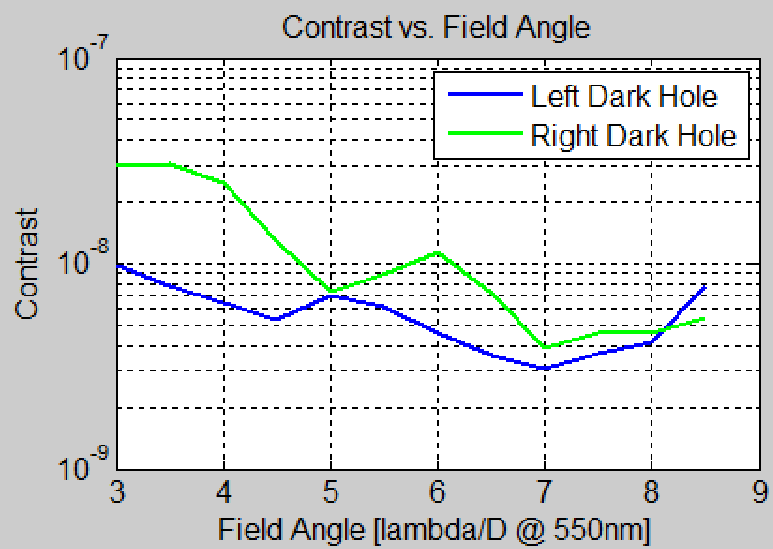
LOWFS/C Dynamic Test Result in SPC Mode



LOWFS/C Dynamic Test in SPC Mode: Movie







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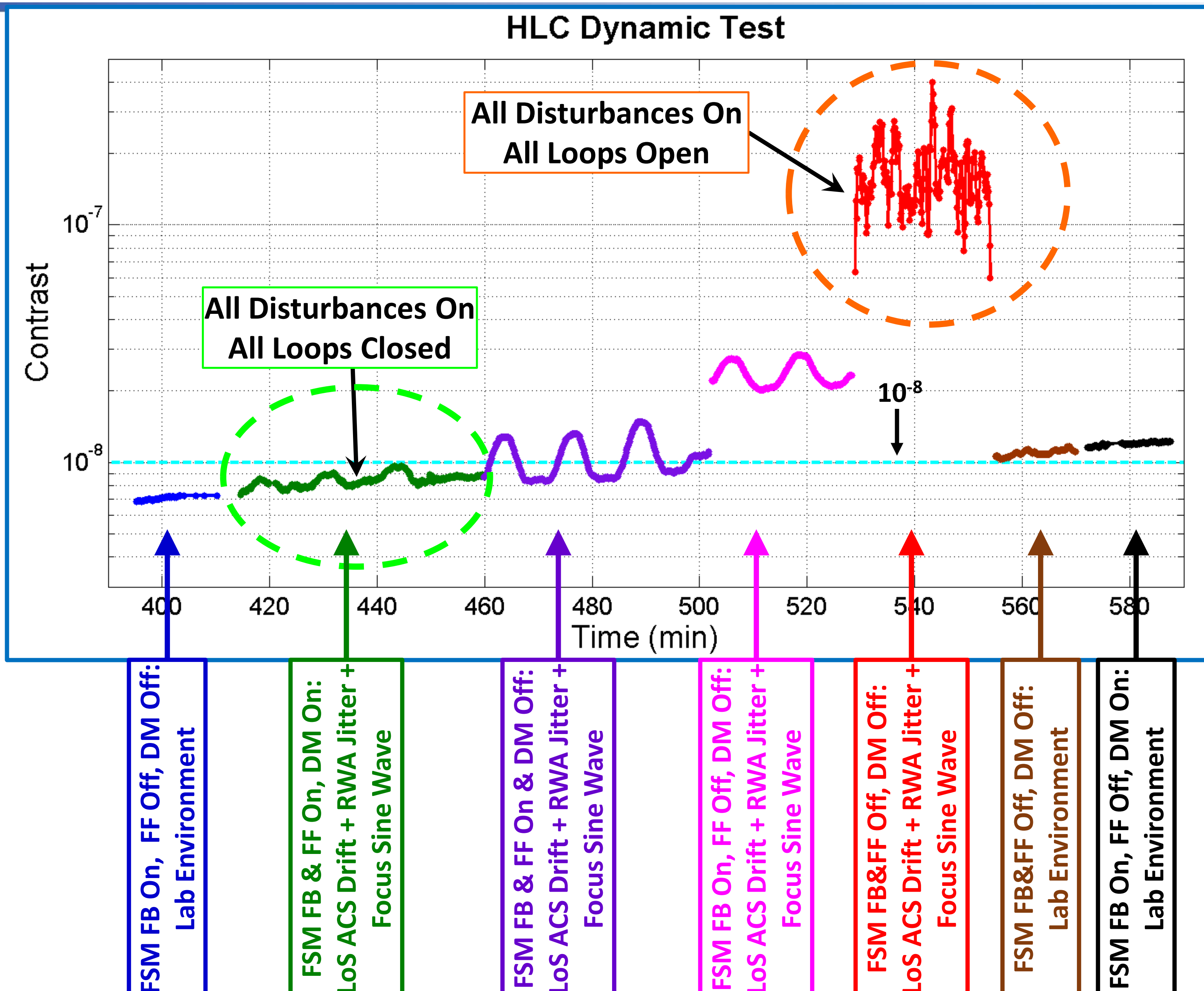
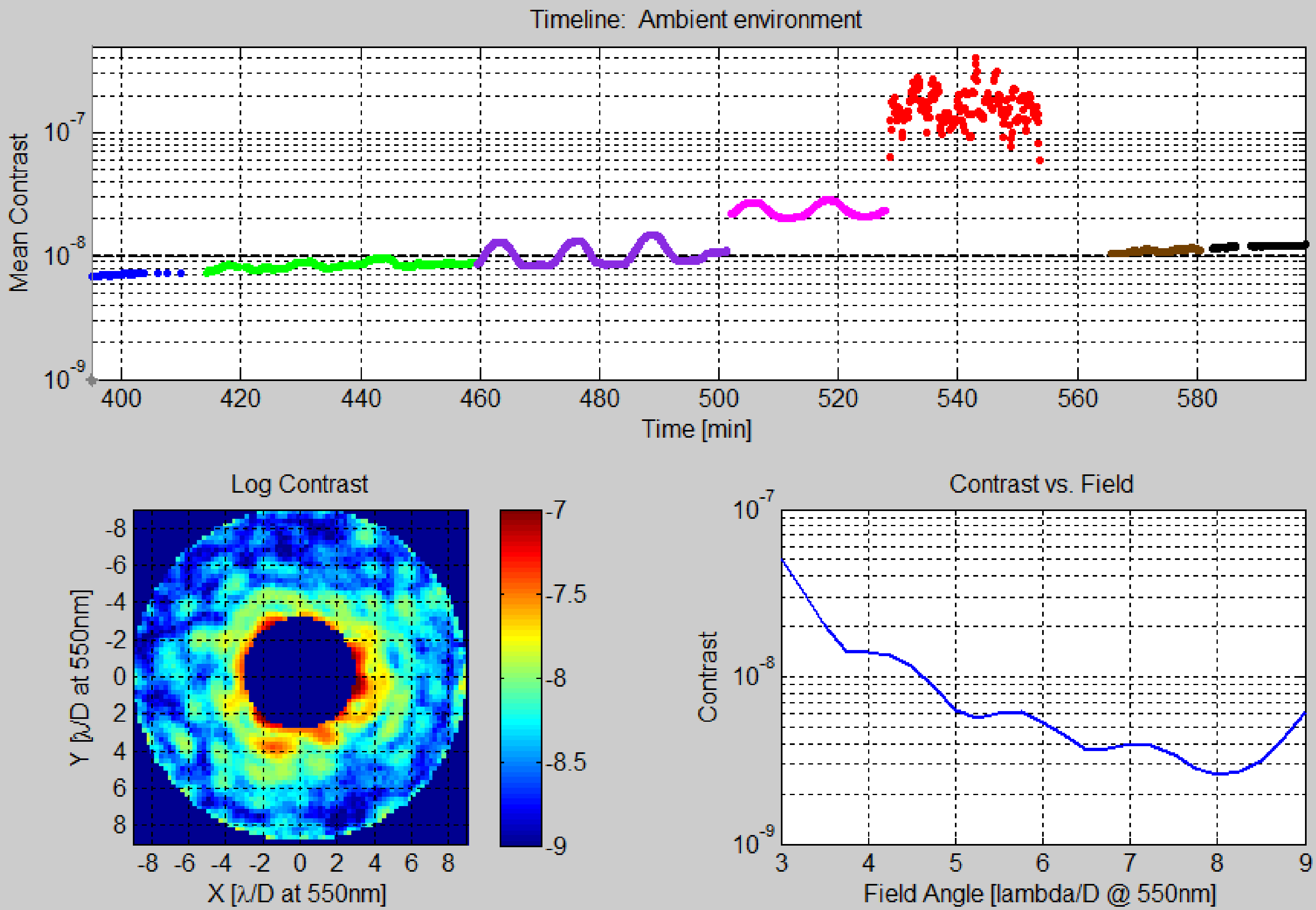
LOWFS/C Dynamic Test Result in HLC Mode



LOWFS/C Dynamic Test in HLC Mode: Movie



HLC LOWFS LoS Correction: Data vs. Model

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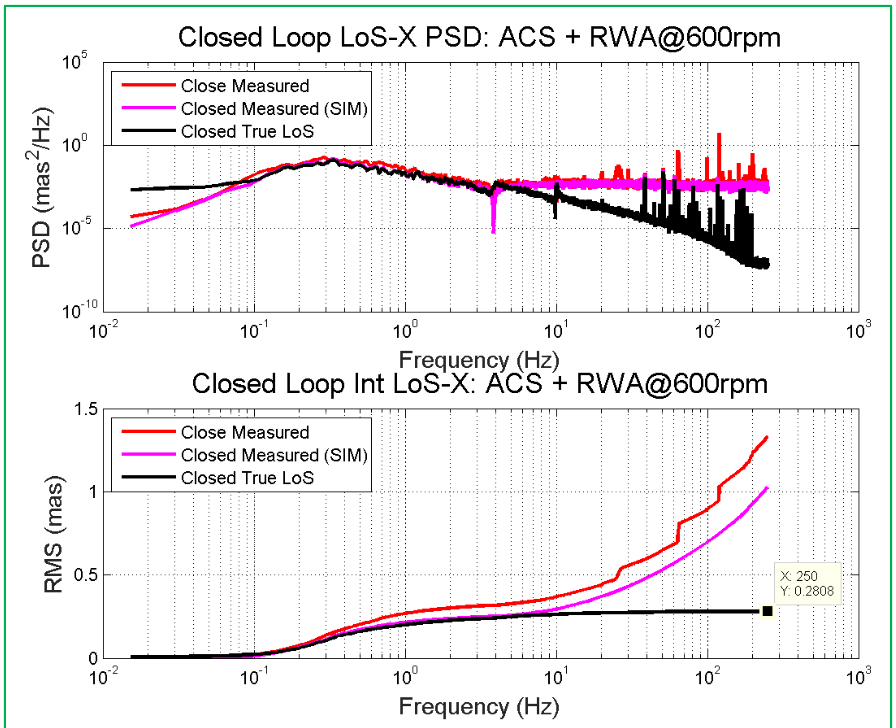
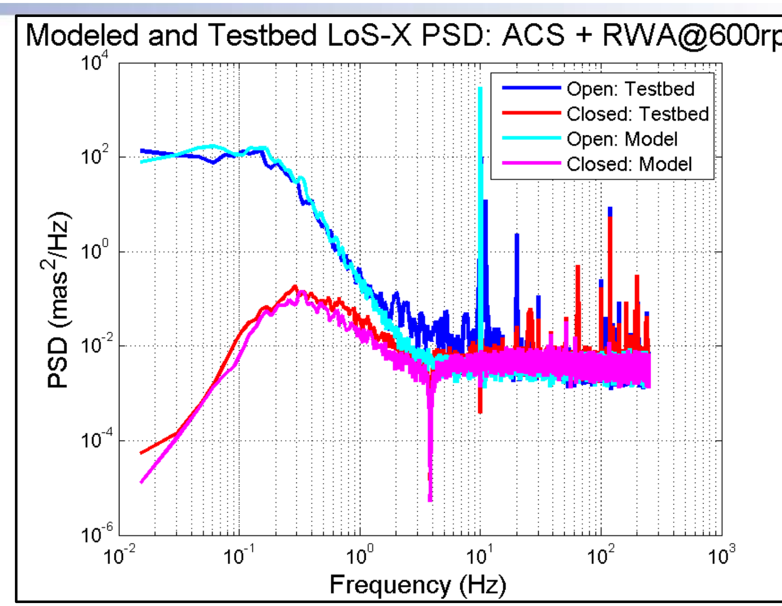
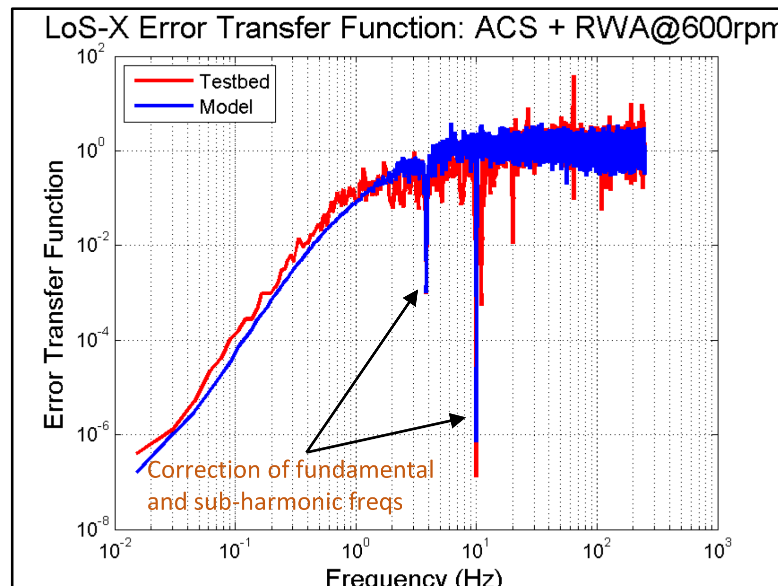
- **Modeled and testbed PSD of open/closed loop in LoS X (upper right plot)**
  - Cycle 5 ACS drift and jitter at wheel speed of 600 rpm
  - Testbed data include lab environment LoS noise
  - Modeled data include sensor noise
- **Modeled and testbed LoS error transfer function calculated from the open and closed loop PSD (lower right plot)**
- **Model predicted true residual LoS-X error without broadband sensor noise (black line below)**
  - FSM loop is not closed on high frequency sensor noise, thus it does not impact loop performance



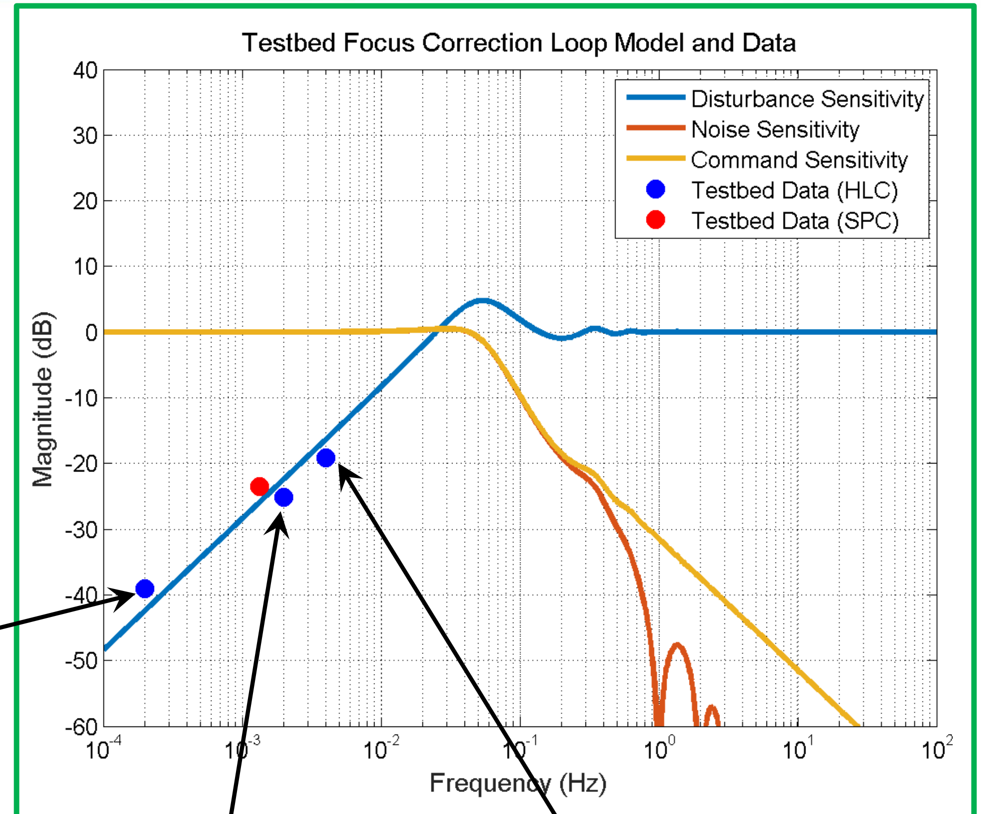


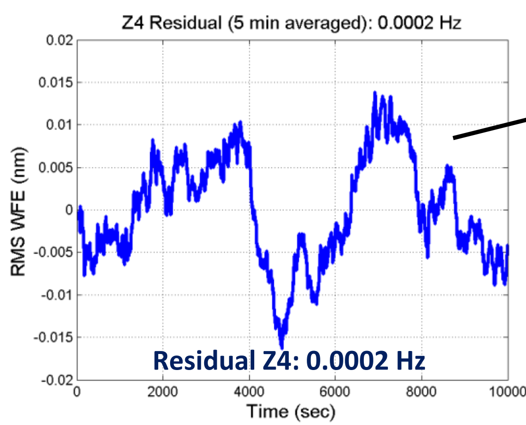


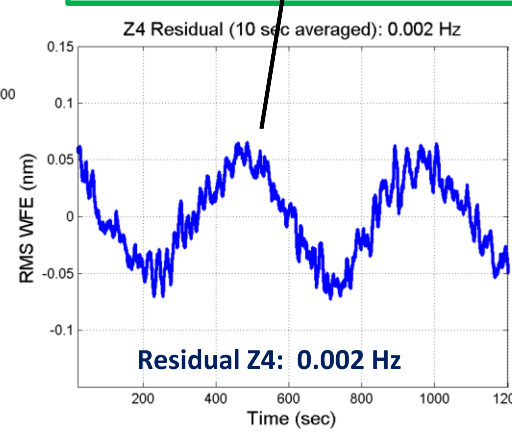
Excellent agreement between modeled and measured LoS loop performance

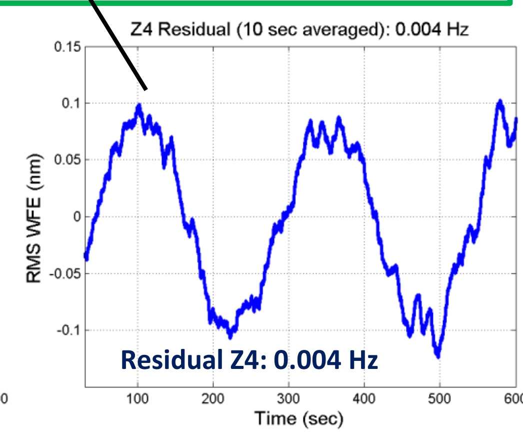
LOWFS/C WFE Sensing and Control: Focus

- Focus drift generated by OTA simulator
  - 2 nm P-V sinusoidal disturbance
  - 4X larger than WFIRST flight
- DM #1 used to correct focus
- **Testbed data matches control model prediction**









Dynamic Testing Conclusions

- Calibrated OTA simulator was used as the disturbance generator and to independently verify LOWFS sensor performance
- LOWFS sensor has demonstrated sensing of LoS tilt to the level of 0.2 mas and low order mode to the level of 12 pm rms
- LOWFS/C can maintain CGI contrast stability to better than 10^{-8} in presence of WFIRST like LoS and low order WFE disturbances in both SPC and HLC modes
  - Three wavefront aberration modes demonstrated (tip-tilt and focus) are the dominant disturbances for WFIRST Coronagraph
  - LOWFS/C correction greatly improves OMC contrast stability
- Simultaneous LoS correction using the FSM and low order wavefront correction using a DM were demonstrated
  - Closed loop LoS residual meets 0.5 mas rms per axis requirement
  - LoS and focus error correction demonstrated in both HLC and SPC modes

Testbed Future Work

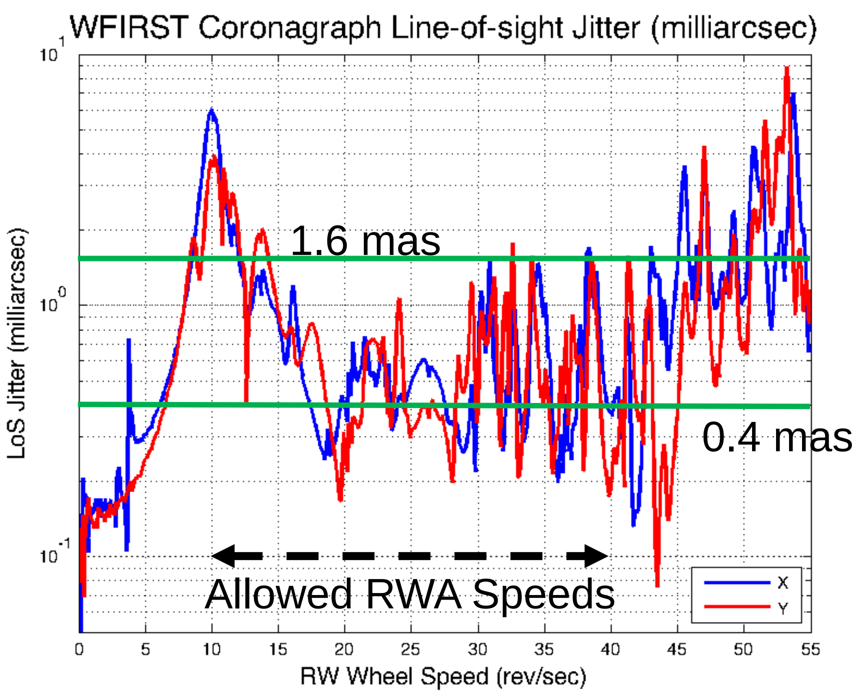
- OMC tests with WFIRST flight like operation configuration
- Further improvement of coronagraph performance, wavefront control algorithms, calibration, efficiency, and model matching
- Transition technology development testbed to WFIRST CGI instrument engineering testbed to test flight hardware and algorithms, and support WFIRST CGI instrument I&T

Backup Slides

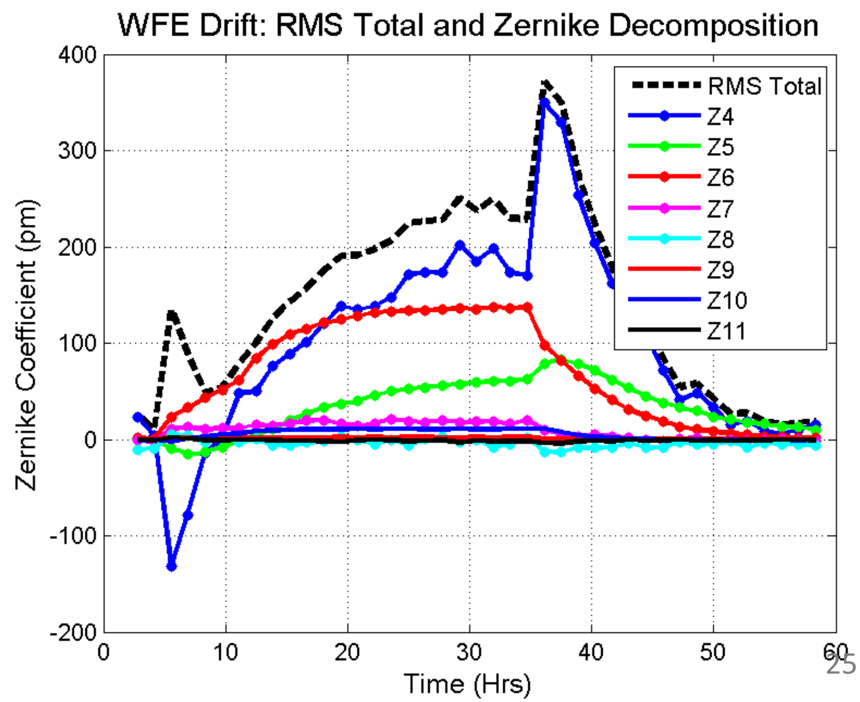
WFIRST Telescope LoS Jitter and WFE Drift

- **Line-of-sight drift and jitter (Cycle 5)**
  - Drift (<2Hz): ~14 milli-arcsec ACS pointing.
  - Jitter (>2Hz): < 10 milli-arcsec. Peaks ~10 Hz, multiple harmonics at each reaction wheel assembly (RWA) wheel speed.
  - WFIRST observatory requirements allow 14 mas drift and 14 mas jitter (rms per axis)
- **WFE drift (Cycle 5)**
  - Mostly thermally induced rigid body motion of the telescope optics when the telescope pointing to different targets.
  - Slow varying, typically <10 pm/hour.
  - Dominant WFE are: focus (Z4), astigmatism (Z5, Z6) and coma (Z7, Z8).

LoS vs RWA Speed



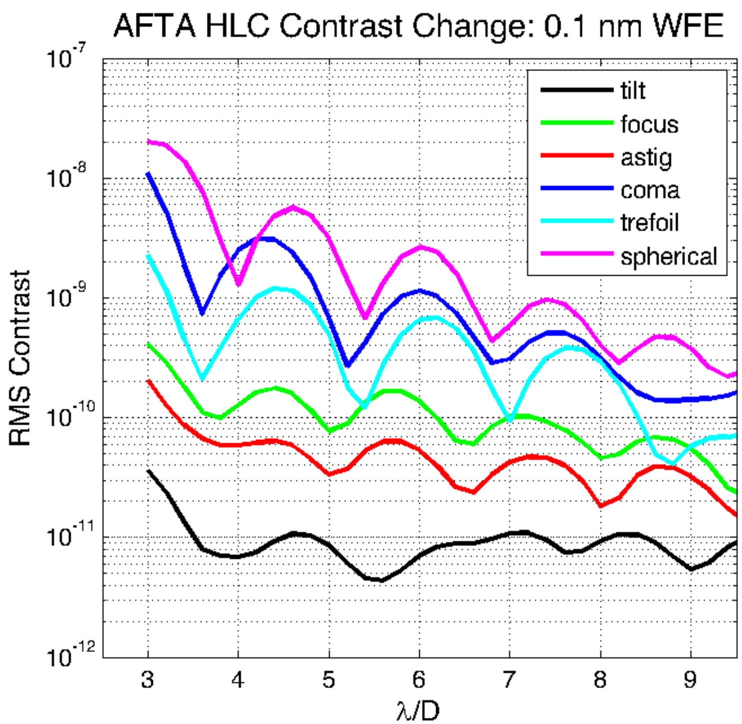
WFE Drift

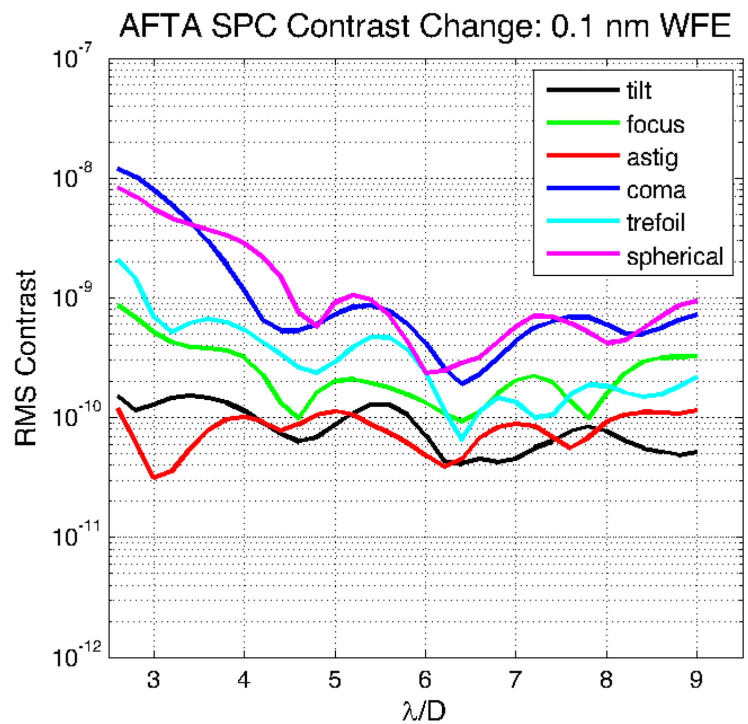


OMC Aberration Sensitivities

HLC and SPC WFE sensitivities modeled by J. Krist

- Compared to 2013 ACWG downselect, HLC sensitivities are lower, SPC sensitivities higher (performance trade-off with the addition of Lyot stop)
- Sensitivity highest to spherical and coma





Impact of Pointing Jitter on OMC Science

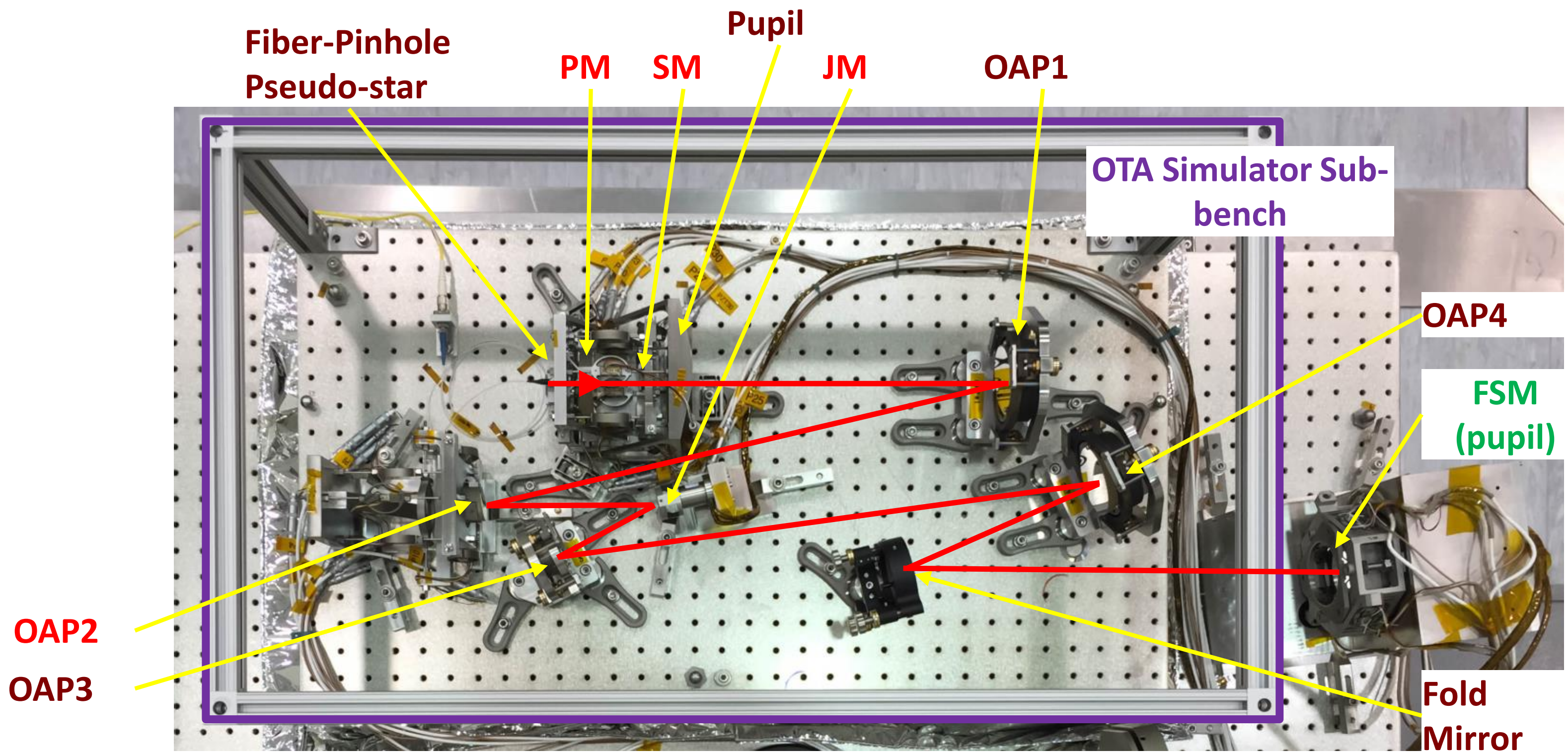
- Number of known RV planets detectable in <1 day by HLC and SPC as a function of jitter and post-processing gain [W. Traub et. al., JATIS, submitted]
- Residual jitter of 1.6 mas rms per axis allows OMC to produce compelling science; selected as the requirement
- Residual jitter of 0.4 mas rms per axis selected as the goal

RMS jitter (mas)	post-processing factor (fpp)	# RV planets detected by HLC in <1 day each	# RV planets detected by SPC in <1 day each
1.6	10	13	11
0.8	10	14	13
0.4	10	14	14

1.6	30	14	15
0.8	30	15	15
0.4	30	15	15

OTA Simulator for OMC Testbed

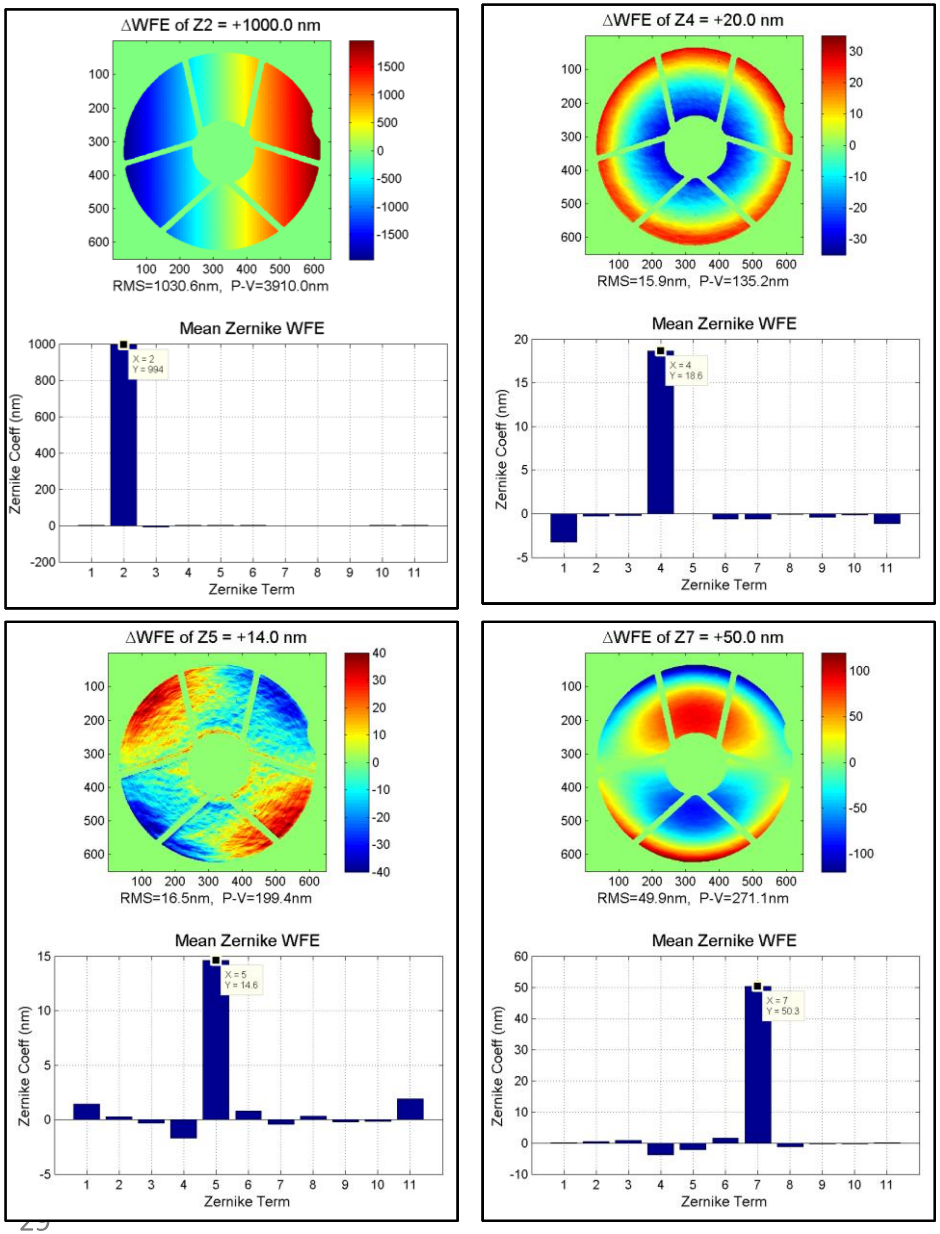
- **OTA Simulator (OTA-S) is used to inject line-of-sight (tip/tilt) and low order aberration drifts into the coronagraph for the dynamic test**
  - Jitter Mirror is used to inject LoS drift and jitter
  - PZT actuators on the OTA-S telescope and OAP2 are used to inject the low order aberrations (focus, astigmatism, coma)
  - OTA-S LoS and low order WFE modes have been calibrated by Zygo interferometer
- **FSM and DM #1 are used to correct LoS and low order WF error, respectively**



Calibration of OTA Simulator

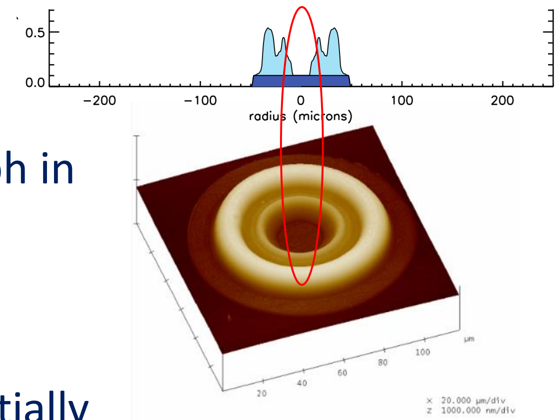
- **OTA Simulator is used to generate WF aberrations and verify ZWFS performance**
- **Low order WFE modes are generated by small rigid body motion of powered optics using PZTs**
  - LoS tilts (dynamic): Z2 and Z3
  - Low order WFE: Z4 (focus), Z5 & Z6 (astigmatism), Z7 & Z8 (coma), Z11 (spherical)
- **Zygo in-air calibrations (double pass)**
  - Influence function of each PZT actuator.
  - Pure WFE modes Zygo measurement (double pass)
    - $\Delta OPD = Aberrated_{OPD} - Nominal_{OPD}$

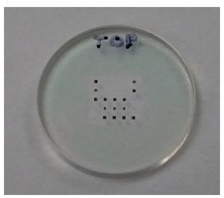
OTA simulator calibrations are used to generate sub-nanometer (rms) WF errors expected on orbit

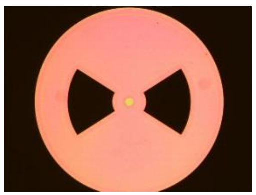


Key LOWFS/C Hardware

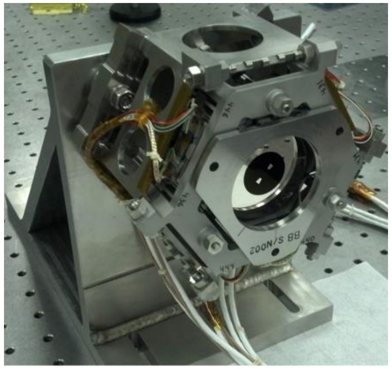
- **Coronagraph/LOWFS focal plane masks**
  - HLC/LOWFS occulter
    - Harder case: occulter center used for coronagraph in transmission, LOWFS in reflections. Performance validated: nulling (MS 5) and LOWFS (MS 6)
  - SPC/LOWFS occulter
    - Easier case: coronagraph and LOWFS regions spatially separated on occulter
  - Both masks fabricated at JPL's MicroDevices Lab





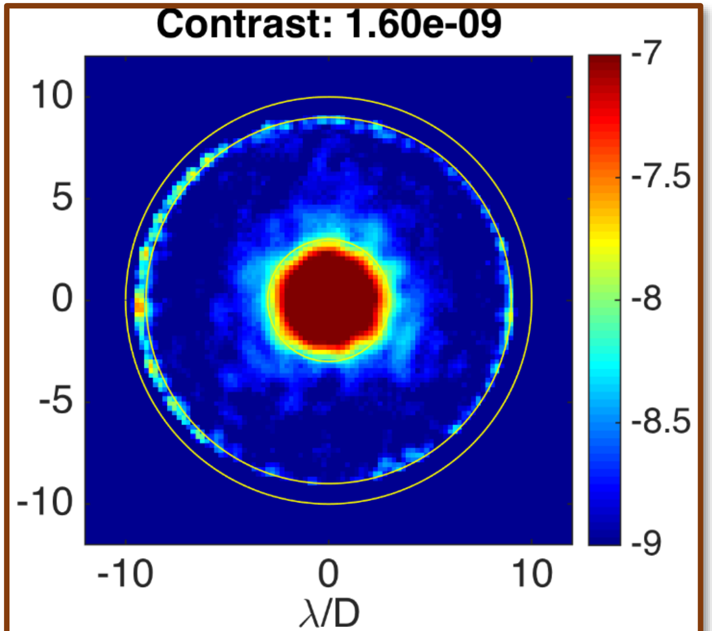


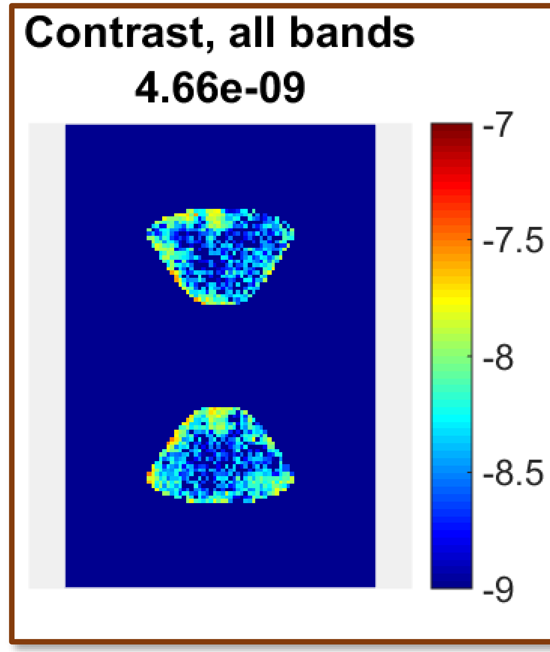
- **LOWFS camera. Used CCD39 for initial demo**
  - SciMeasure camera electronics implementation does not meet its 7.5e- read noise spec at 1kHz
  - Options that meet spec exist with no new technology (engineering only)
- **Fast Steering Mirror. High TRL unit built for SIM**
  - Performance extensively characterized for WFIRST



High TRL for key LOWFS hardware

Best Static Contrast: SPC and HLC



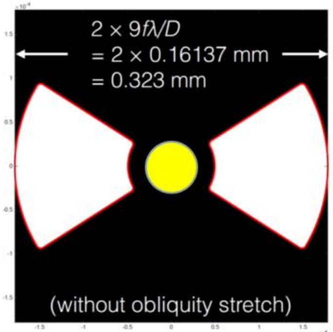


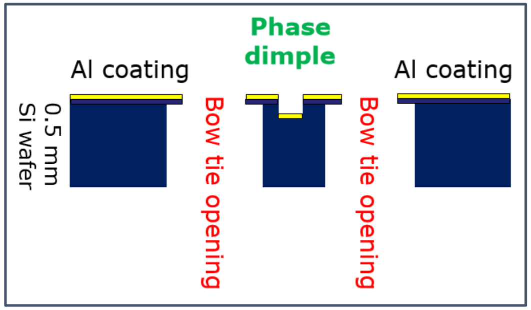
- **OMC testbed static contrast has significantly improved for both HLC and SPC modes**
- **Latest contrast results (10% bandwidth at 550 nm): SPC = 4.66×10^{-9} and HLC = 1.60×10^{-9}**
  - Better wavefront control algorithm by alternating the EFC control aggressiveness (regularization). SPC has not had opportunity to test this approach yet.
  - Replaced the commercial metallic, laser-burnt pinhole with a pinhole made at JPL using e-beam lithography, etched in a thin silicon wafer.
  - Reduced testbed LoS jitter by turning off the strain gauges on jitter mirror and fast steering mirror

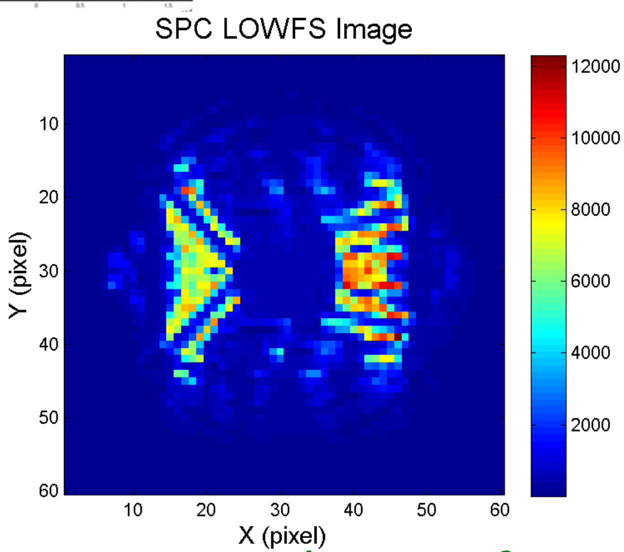
Excellent static contrast level achieved with WFIRST aperture for HLC and SPC

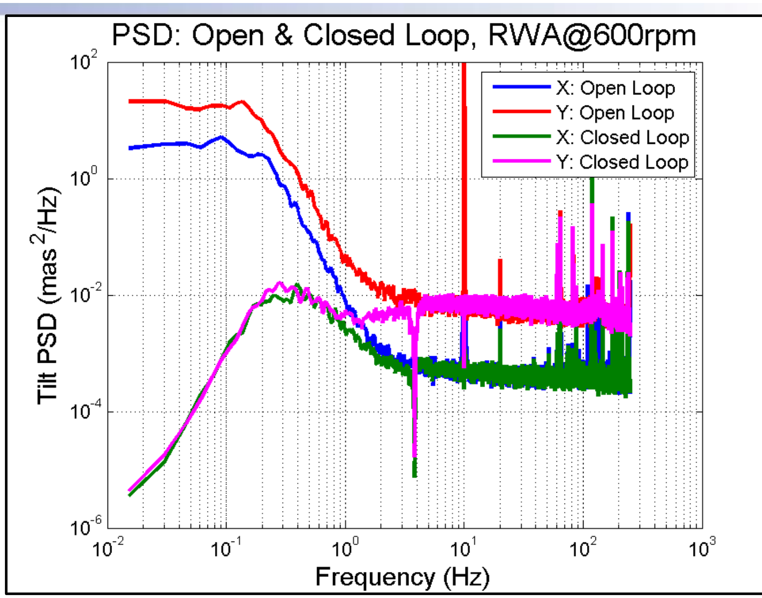
SPC LOWFS Line-of-Sight Correction

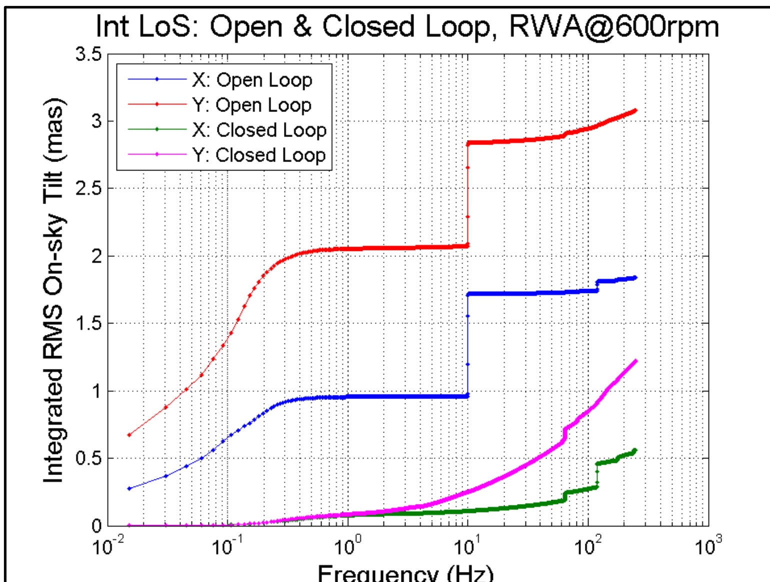
- Zernike phase dimple built into new SPC “bowtie” occulting masks, fabricated at JPL’s MDL
- Cycle 5 CBE LoS disturbances tested on the OMC testbed
- Residual error is dominated by the LOWFS sensor noise and testbed environment noise
  - Asymmetric SPC PSF causes more sensor noise in Y









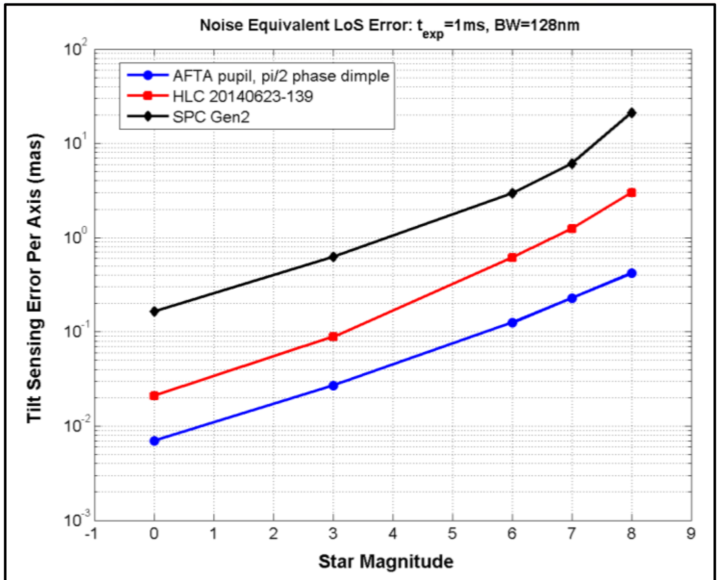


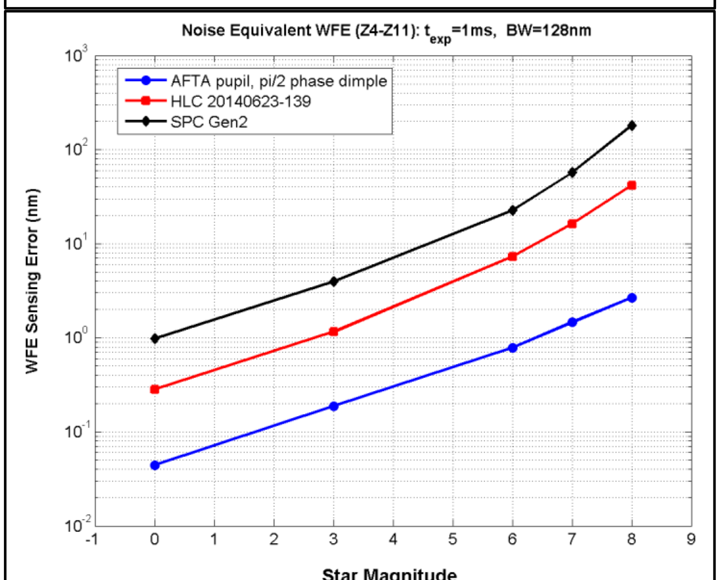
LoS correction loop performs well in both SPC and HLC modes

ZWFS Modeling and Performance Analysis

Jet Propulsion Laboratory
California Institute of Technology

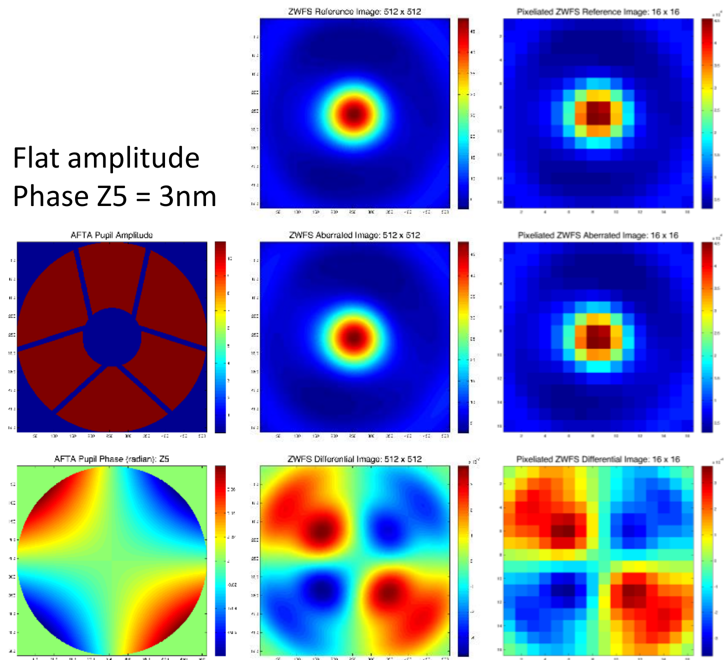
ZWFS Noise Equivalent Sensing Error





- **Diffraction models of ZWFS for HLC and SPC used to analyze the ZWFS performance**
- **ZWFS noise equivalent errors (LoS and WFE)**
  - PSF difference caused by diffraction (SPC) or DMs (HLC) increases the ZWFS sensing error
  - Plots on the left is ZWFS @ 1 msec exposure (CCD readout at 1 KHz)
    - For slow varying WFE, image averaging will lower the equivalent M_V

Sample Images of HLC/ZWFS



WFIRST CGI LOWFS performance has been extensively modeled